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13. ABSTRACT (Maximum 200 words) This quarterly report provides a summary of support provided by the Institute for Advanced Technology (IAT) at The University of Texas at Austin (UT) to the Office of Naval Research (ONR) on the development of high-power superconducting homopolar motors for ship propulsion. One of the major issues facing the development of such machines for ship propulsion is the lifetime of the brushes used to transfer power from the homopolar motor rotor to the stator. Significant loss and wear polarity differences have been observed during the testing of such brushes, and ONR is developing a fundamental science program to address these issues. During this quarter, IAT personnel participated in an integrated product team (IPT) meeting, giving impromptu presentations on historical aspects of fiber brush development and providing written comments to the ONR program manager afterward. In addition, IAT personnel reviewed weekly data reports provided by General Atomics (GA).		
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Quarterly Progress Report

Period of Performance:

March 1, 2004–May 31, 2005

Prepared by:

**Dr. Ian McNab
Principal Investigator**

**Institute for Advanced Technology
The University of Texas at Austin
3925 W. Braker Ln., Suite 400
Austin, TX 78759**

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K. Seward, ONR N66018
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QUARTERLY PROGRESS SUMMARY REPORT
Period reported: March 1, 2005 through May 31, 2005

1. Contract Summary

- Grant number: N00014-05-1-0123
- Period of performance: December 1, 2004 to October 31, 2005
- Total value of awarded Grant: \$75,000.00
- Option No. 1: \$75,000.00 for period November 1, 2005 to October 31, 2006
- Option No. 2: \$75,000.00 for period November 1, 2006 to October 31, 2007

2. Contract Personnel

The Key Personnel involved in this effort are Dr. Ian R. McNab, Principal Investigator, and Dr. Chadee Persad. Dr. McNab is a Senior Research Scientist at The University of Texas at Austin and Director of the Electromagnetic Systems Division (ESD) at the Institute for Advanced Technology (IAT). He has had extensive prior experience and involvement in superconducting homopolar generators and motors and in the development of fiber and other brushes for these and similar machines. Dr. Persad is also a Senior Research Scientist at UT and is the Team Leader on High-Performance Materials at the IAT. From time to time, other technical experts working at the IAT who have relevant technical expertise may be consulted for comments and advice relating to this effort. The chief experts are Dr. John A. Mallick and Dr. Kuo-Ta Hsieh. Dr. Mallick is a Research Scientist at UT and an expert in electrical machines. He is the Team Leader for Pulsed Power at the IAT. He has had extensive involvement in superconducting machines during his career at General Electric. Dr. Hsieh is a Research Scientist at UT and is co-Team Leader for the Analysis and Code Development Section of the ESD. He is an expert on the development of high-capability codes and advanced computing. Following the call for, and evaluation of, proposal activities in January and February 2005, Dr. Hsieh was awarded a separate contract to provide electromagnetic, mechanical and thermal code modeling support to the effort by the Office of Naval Research (ONR) and General Atomics (GA). As a consequence, from April 1, 2005, Dr. Hsieh's support efforts will be reported via that contract.

3. Technical Report

3.1. Background

The support being provided by the IAT experts for ONR on this program is focused on the issues relating to the brushes being used and developed to transfer the load current to the superconducting homopolar motors being developed by GA for ship propulsion. In common with earlier experience in the brush field, significant polarity differences have been observed during brush system tests at GA, the prime contractor for ONR on this program. The fundamental reasons for these polarity differences are not well understood, despite there having been many attempts to explain the effects. Generally it is found that the brush having a positive polarity operates with significantly higher voltage drop and wear rate than the brush having a negative polarity. From the GA data, it seems that the negative brushes will have a lifetime that is acceptable for fleet operation, but the wear rate of the positive brushes is too high and may demand more frequent replacement than can be tolerated.

3.2. Integrated Project Team

Under the auspices of this grant, the IAT has been invited to participate in meetings of the integrated product team (IPT) set up by ONR with GA. These meetings are generally scheduled on a monthly basis. During this quarterly period, Drs. McNab, Persad and Hsieh attended a major review meeting at GA in San Diego on May 3 and 4, 2005. During this meeting, Drs. McNab and Persad gave impromptu presentations on historical aspects of fiber brush development and analysis of GA brush debris, respectively.

3.3. General Atomics Review, May 3–4, 2005.

Following attendance at this meeting, Drs. McNab, Persad and Hsieh provided written comments to the ONR Program manager, Mr. Steven Schreppler. These are included here as Appendices A, B and C. Later in May, Dr. McNab reviewed the GA HPM 10-Turn SSM Test Plan and provided supporting comments to Mr. Roy Dunnington of Anteon.

3.4. GA data

Drs. McNab and Persad reviewed the weekly data reports provided by GA in preparation for the meeting scheduled for May 3–5, 2005 at GA.

3.5. Early Work on Fiber Brushes

In addition to the early work carried out by Dr. McNab and others (which was presented at the February 2004 meeting) some other early work in the fundamentals of fiber brushes was carried out in the UK under the auspices of an MOD(N) cooperative project. One output from that was some modeling of single (carbon) fibers undertaken by Mr. P. K. C. Wiggs of Morganite Carbon in 1971, as described in the attached paper.

4. Expenditures:

See financial attachment.

APPENDIX A

Memo to: Steve Schreppler (ONR)
Subject: IPT Meeting and Quarterly Progress Review (May 3rd and 4th, 2005)
From: Ian R. McNab
Date: May 10, 2005

Steve,

A few informal and general comments on the meetings last week:

1. You have established an excellent group of relevant academic and industrial experts to support the brush studies. It is important to keep the group focused on the objectives and having a steering committee is a good way to do that. There should be scope in the program for a separate meeting—maybe two or three days in length—in which some of the fundamentals of brush operation are discussed in more detail. We would be happy to host such a meeting here at IAT-UT if that would be helpful.
2. There are clearly a large number of approaches that can be followed in the fundamental studies. In parallel with the studies of the multi-fiber brushes, I would like to stress in our work the idea of building up data on single and then a few fibers, so that we can build a brush “from the ground up,” so to speak.
3. I do not see any reason for there to be any mechanically induced polarity effects.
4. Electro-migration is an effect that has been observed at very high current densities. While the overall brush current densities do not approach the levels required for electro-migration, perhaps it could be possible that the tips of individual fibers might reach these levels.
5. Based on prior experience, you should expect that, as the testing gets into larger numbers of brushes, things will get worse—e.g., higher wear rates and more debris will be experienced. Some of this will be exponential in the sense that more brushes and longer operation will both result in more wear debris (from the slipring as well as the brush), some of which will stay in the brush, so it will become more solid and less flexible and therefore less able to accommodate slipring surface variations.
6. The comment was made that the goal is to eliminate the protective atmosphere presently used for the brushes. While I agree that this should be the goal, I don't think that it is very likely. In any case, there will probably be a need to enclose the machine for other reasons—to enable effective cooling to be introduced and to prevent brush debris from migrating into the ship environment and doing unpleasant things to equipment or the crew.
7. As I mentioned several times, I think it would be good to measure the slipring eccentricity on a continuous basis. I also think that a priority for the academic team should be to develop a sensor that is capable of monitoring the slipring surface conditions, especially including temperature, reflectance and roughness. Note that as larger numbers of brushes are used, wear of the slipring itself could become an issue.
8. As we discussed in the hotel on Wednesday evening, having the capability for the machine to shut down quickly when a problem develops is very important. Going along with that is the need to remediate the slipring if a problem has occurred. To do this in situ implies that at least a smoothing capability should be provided on each slipring track—maybe with a light

sanding capability. Of course, such a capability should be carefully designed so as not to introduce abrasive debris that would cause even more wear later. Being able to demonstrate both the sensing and the remediation capability in a smaller test rig would be a good objective.

9. A separate but related issue is that every effort should be made to ensure that there are as many data channels as possible for the brush testers and the machines. More data is always going to be helpful. The instrumentation budget should reflect this, especially where fast signals are needed.
10. During this program, I have mentioned several times that I think it would be possible, as with other superconducting homopolar machines, to match the slipring surface angles to the magnetic field vector to eliminate circulating currents. This will never be completely effective if the magnetic field changes, but it could help a lot to reduce twisting forces on the brushes and to reduce local current densities at the brush-slipring interface. This would introduce some additional machining cost. I understand that the decision has now been made not to do this, as the circulating currents are smaller than had earlier been expected, and the forces are considered manageable. Nevertheless, the circulating currents do add to the brush burden, and this should still be held as an option if brush performance and life continue to be a concern.
11. While I don't think that an AC ripple on the DC power feed to the brushes should introduce any bad effects, it would probably be better if it could be eliminated as much as possible.
12. Similarly, I don't think that transient effects during start-up and shutdown should have a big effect on brush performance, but it would be good to characterize them anyway.
13. The main issue I had with the meeting, on later reflection, is that I am not sure that there is enough room for innovative concepts to be brought into the program. This is a tough balance for the program manager to make—there is always pressure to perform with the “core” concepts, so there is corresponding reluctance to “divert” the program to try innovative concepts. It might be useful to set aside one or more of the test rigs that are to be brought on line by Neal Sondergaard as test rigs specifically to screen new concepts to establish confidence prior to introducing them into the main GA machines.
14. In the non-brush area, the “new” approach on coil cooling seems to raise some significant issues for the Navy. Spending 10+ days to cool the magnets down might just be acceptable, I suppose, for a planned deployment. For anything other than that, it sounds as though it may be necessary to keep the machines at cryotemperatures and accept the cooling burden and losses. More worrying is the need for > 24 hours to get back to operation after a quench has occurred. It does not seem likely that this would be acceptable in combat.

I hope that these comments are of some help. Thank you for inviting Drs. Persad and Hsieh and me to the meeting.

Best regards,

Ian McNab

APPENDIX B

Memo to: Steve Schreppler (ONR)
Subject: IPT Meeting and Quarterly Progress Review (May 3rd and 4th, 2005)
From: Chadee Persad
Date: May 11, 2005

Dear Steve:

Here is my set of bullets with notes on the recent ONR HPM Progress Review hosted by GA.

The focus is on contact materials performance issues, and on brush tribology.

I. Brush IPT Meeting, General Atomics, San Diego, CA, May 3, 2005

1. Need to Standardize Terminology There is a clear need to use a common set of terms to describe brush durability. An approach is given by Rawls et al, 1989¹. Two useful concepts are described. Wear index is the average increase in brush-head dimensions. Wear rating is a means of classifying the increasing severity of functional deterioration.
2. Arcing Contact In the brush forensics study some brush tips show arcing damage. Flinders et al, 1999² used video camera images of sparking at brush-commutator interfaces to reveal the relationship between harmonic currents and mechanical vibrations in DC motors. They concluded that the mechanical resonances of motors at certain speeds is a major cause of excessive brush and commutator wear. [Responding to our recent request at the IPT meeting, GA has already provided us with additional wear debris samples for analysis. These samples are from their April 2005 tests. We plan to look carefully for evidence of arcing-induced debris.]
3. Role of Humidified Carbon Dioxide While many questions remain about the possible role of humidified carbon dioxide in asymmetric brush wear, it appears that our preliminary findings of the presence of a hydrated copper carbonate that we reported in Nov 2004 have now been independently confirmed by three other research groups. We have now also disclosed a possible connection between the level of hydration of copper carbonate and its associated work function {0 – 35 mV}. The illustrative data for ten carbonates was reported by Ostrick et al, 1999³.

II. ONR Program Review #11, Homopolar Motor, San Diego, CA, May 4, 2005

1. Measurements and Instrumentation There is at least one mass measurement that should be attempted to reliably show the mass loss/gain of each brush by comparing measured mass before test, and that at the end of a test series. In addition, while it is clearly difficult to have a method for direct observation of slip ring tracks during testing, it should be possible during

¹ H. R. Rawls et al., *J. Dent. Res.* 68(12):1781-1785, December 1989 (Hard copy given to Dr. Blake).

² F. Flinders et al., IEEE 1999 Int. Conf. on Power Electronics & Drive Systems, PEDS'99, July 1999, Hong Kong.

³ B. Ostrick et al., "Adsorbed water as key to room temperature gas-sensitive reactions in work function type sensors: the carbonate-carbon dioxide system," *Sensors and Actuators B: Chemical* vol. 57 pp. 115-119, 1999.

non-teardown inspections to produce an optical record of the condition of a wear track referenced to an arbitrary "theta equals zero" position on a slip ring. We have found the system made by Keyence to be capable of producing optical images with significant depth of field. It uses a phase-stepping laser interferometer, digital microscope, and computer-controlled profilometer⁴.

2. New Alloy for SSI Fiber Brushes Dr. S. Pourrahi of SSI mentioned his work on copper-silver alloy fibers for future HPM brushes during our discussion of May 3. Since UT has been conducting high-current testing of a copper-silver alloy for rail conductor applications, and we now have a model for microstructural control of strength in this alloy, we agreed to visit the SSI facilities and to share our test data on this Cu-Ag alloy.
3. Thermal model for sliding interface and adjacent rotor/stator structure We have identified the need for more detailed modeling of the "electro-thermal circuit" that produces and transports heat away from the brush/rotor interface. The sparse, remote, single-point measurement of temperature that is now made is clearly insufficient to describe the volumetric temperature field and its relationship to brush durability. A faculty member at the Naval Postgraduate School with extensive experience in the FE modeling of heat transfer in metal pin arrays has expressed interest in the problem. We plan to seek the support of the IPT to initiate an effort in this area.
4. Robustness of Insulation System While not much attention is being paid to the insulation system in the initial stages of the GA plan, it will become important to characterize the long term stability of the thin layer of insulation material in the full-scale rotor operating environment. Issues such as the long-term effects of moisture on epoxy-based insulation systems should be considered, and the lessons learned in other DoD S&T programs should be captured.

Thanks for presenting us with a challenging S&T problem, and for assembling a strong multi-disciplinary team to tackle it. I would be happy to hear other views and to discuss any of these topics with other interested parties.

Best Regards,

Chadee Persad

⁴ Atanasov, P. A. et al., "Aspects of CO₂ Laser Engraving of Printing Cylinders," *Applied Optics LP*, vol. 38, iss. 9, pp.1759-1763, 1999.

APPENDIX C

Memo to: Steve Schreppler (ONR)
Subject: IPT Meeting and Quarterly Progress Review (May 3rd and 4th, 2005)
From: Kuo-Ta Hsieh
Date: 11th May 2005

Dear Steve,

Thanks for inviting me to the IPT meeting at GA. The followings are few notes for the meeting:

1. The meeting was very informative and will help the PI's to become familiar with the program and associated critical issues.
2. The PI presentation that described each PI's expertise and the planned work is useful to all attendees, and it also lays the foundation for future collaboration. During the meeting, I had the chance to chat with Dr. Rudolph Martinez (Anteon), Mrs. Paula Zivi (Anteon), and Dr. Neal Sondergaard (NSWC/CD). These investigators were referred to me by Mr. Roy Dunnington per your instruction for potential collaboration. In particular, Paula and I have agreed to regularly exchange information related to the modeling efforts, emphasizing the use of a common material property data, and the continuous comparison and refinement of our models and simulation results.
3. GA has done a great job in conducting hundreds of brush tests. However, to harmonize the effort to interpret the test results, as I suggested to you in the meeting, we should define a common experiment for the modelers to benchmark their numerical models. The validated model then could be used to investigate the critical issues and predict the performance of full scale motor in the future. Such an experiment should meet the following criteria:
 - a. Conducted under the real operating conditions including the effects of rotation, transport current and operating magnetic field to catch all related phenomena.
 - b. Complete characterization of electromagnetic (electric conductivity; temperature dependent and anisotropic), thermal (thermal specific heat and thermal conductivity), and mechanical (yield strength, elastic modules; thermal dependent and anisotropic) material properties of key components such as the brush, slip ring, rotor, field coil and iron if any. These data are critical for the solutions of the model to be accurate.
 - c. Is well-documented including the geometry and initial and final dimensions of key components, operating conditions and measured diagnostic data.

The sub-scale tests of either one turn or ten turns could be a good candidate. Your involvement will help to make it happen smoothly and sooner.

Best Regards,

Kuo-Ta Hsieh

Measurement of Friction and Contact Resistance of a Single Carbon Fibre Running Against a Copper Ring

by P. K. C. Wiggs

Morganite Carbon Ltd., Battersea Church Road, London, S.W.11

(Manuscript received 17 August, 1970)

The friction and constant drop of a single fibre, acting as a brush, was measured, the fibre acting as its own dynamometer. Under such conditions, no co-operative effects between adjacent fibres could occur.

Introduction

IN the early days of electric motors and generators, the 'brushes' were literally wire brushes. Later these were replaced by compacted gauze, and then by solid blocks of carbon, but the name of 'brush' was retained. With the development of high-modulus carbon fibres, an attempt has been made to return to the original fibrous brush, with its multiple independent collecting points.

In some of the early experiments, made in co-operation with the Admiralty Materials Laboratory,¹ brushes containing about 3×10^6 fibres were run against silver and copper counter-faces, moving at speeds between 10 and 40 m/sec. With free-fibre lengths of a few mm, loads of the order of 1N were necessary to maintain contact without excessive deformation of the fibres. Under these conditions, the coefficient of friction was usually near unity, but on some occasions the value rose to a level as high as 9. The electrical contact drop was also erratic, though it showed many of the non-linear features of solid-carbon brushes, with rather higher values.

In order to contribute to the understanding of these effects, it was decided to use a single fibre as a brush, and so to measure the friction and constant drop under conditions in which no co-operative effects between adjacent fibres could occur. The problem was to measure the coefficient of friction in a system in which the vertical force between the rubbing members was only a few μ N. The solution was to use the fibre as its own dynamometer, in which the exact curvature taken up by the fibre was an indication of the ratio of horizontal to vertical reactions at the contact.

Experimental

A single high-modulus carbon fibre, 7 μ m in diameter, was suspended vertically with a weight on its lower end: while in this position it was stuck with conductive cement to a nut, which could later be attached to the lower end of a vertical slide. When the cement was set, the fibre was cut off to about 5 mm free length: a number of nuts with fibres attached were stored, and suitable ones, with the fibre near the precise vertical, were selected by microscopic examination.

A suitable fibre was attached to the slide, and was lowered slowly towards the face of a copper disc rotating at about 1.2 rev/sec, the radius of the track being about 60 mm. Although the linear velocity was only about 0.4 m/sec, compared with some 40 m/sec in a practical machine, no higher speed was possible as windage disturbed the fibre.

The face and periphery of the disc, except for a narrow track on which the fibre ran, were painted black to assist photography. The fibre was photographed against a black background via a low power horizontal microscope (magnification 16). Two spotlights, on either side of the microscope gave a bright image of the fibre against a dark ground, and allowed exposures of a few seconds to be used.

The electric circuit was completed, from a battery, through fixed and variable resistors adjustable up to several hundred megohms. In all cases the fibre was positive. The current in the circuit was deduced from the potential across an adjustable shunt, chosen to give a p.d. of about 1 V at the required current. Potential drop across the contact was measured between the nut to which the fibre was attached, and the frame of the machine. Both potentials were measured with 0.4 V digital voltmeters, having input resistance of 25 G Ω .

The fibre resistance was of the order of 5 k Ω , so that at 1 μ A the potential drop down the fibre was negligible; but at a current of 50 μ A this was no longer true, and a correction had to be applied to the observed potential difference to estimate the true contact drop.

70 μ A was the upper limit of current, above which the fibre overheated and burnt.

Results

Mechanical

Photographs were taken with fibres lowered to different extents, so varying the contact angle between fibre and disc. It was necessary to identify the point of contact in the photograph, which was easier with a large contact angle, but the shape taken up by the fibre is more sensitive to the value of the coefficient of friction when the contact angle is small. A compromise was therefore made and values of the contact angle between 10 and 20° were adopted (Fig. 1).

The photographs were enlarged so that the vertical distance between the top of the fibre and the disc surface was 152.4 mm (6.0 in). The contact angle was measured from the photograph to the nearest 0.1° and fed into a computer programme, written in FORTRAN, which produced a table of co-ordinates and a graph of the fibre shape for this contact angle, with three different values of the coefficient of friction (0.1, 1.0 and 5.0). The height of the graphs drawn by the computer was also 152.4 mm (6.0 in), so that the fibre form

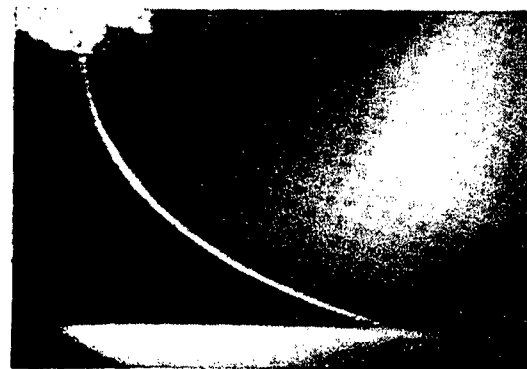


Fig. 1. Photograph of fibre at 19.3° contact angle

from the photographs could be traced directly on to the graph (Fig. 2). By interpolation of the observed form between the calculated curves, it was possible to estimate the coefficient of friction. Also from the mathematics of the fibre form, and the known length and stiffness of the fibre, the vertical force on the surface could be estimated.

Values of the coefficient of friction ranging from 0.5 to 2 were observed, and the vertical force was of the order of 4 μN , corresponding to a pressure of the order of 30 kN/m^2 (4.5 lbf/in^2) calculated on the oblique cross-section of the fibre. The corresponding coefficient for a conventional solid electrographite brush would be of the order of 0.1-0.2.

Mathematical note

The expression for the form of the fibre, an elastic curve, is derived in terms of elliptic integrals, as shown in the Appendix.

The computer, an I.C.L. 1902, was equipped with library routines for the complete integrals of both first and second types (square root in denominator and numerator, respectively) and for the incomplete integral of the first type. For the incomplete integral of the second type, a routine was written in which the expression without the square root was expressed in zones, not more than $\pi/8$ wide, by writing it as a polynomial about the zone centre, using a Taylor series. Each polynomial was then raised to the 0.5 power by means of an I.C.L. library routine, and the new polynomial integrated. The contributions of the several zones were then added.

Electrical

When the current was slowly increased from 0.5 to 70 μA , the contact potential was between 0.5 and 2 V for a fibre trailing at 20° to the counterface. However, on running for some minutes with current passing, the contact potential rose markedly and stabilised at a much higher level, of the order of 3 to 6 V.

It was found that the low-voltage regime could be temporarily re-established by cleaning the counterface with acetone or with abrasive paper, or by moving the fibre slightly in a radial direction.

When measurements were made on a fibre which barely touched the counterface (80° contact angle), contact voltages were somewhat higher, as would be expected with the increased current density over the near circular cross-section

(as opposed to a long ellipse on the fibre rubbing at 20°).

Measurement of contact potential in the static contact gave erratic results, but in most cases the potential was entirely accounted for by the ohmic drop down the fibre, with near perfect contact between fibre and disc.

Table I shows the potential for various values of current in the low- and high-voltage regime.

It is relevant to convert the current values into current-density on the oblique section of the fibre, and to compare the current density *versus* contact potential results with those for a conventional electrographite brush, run at low speed and equivalent pressure (30 $\text{kN/m}^2 = 4.5 \text{ lbf/in}^2$). Table II shows the values.

It is possible to match values if the current density for the solid brush is multiplied by 5 and the voltage by 1.2 to obtain the low-voltage fibre figures, and the current by 10 and the voltage by 3.5 for the high-voltage figures. It is hoped to incorporate these factors in a general theory of brush contacts. The major differences, apart from linear scale, between the fibre and solid-brush contacts, are the transit times of the order of 80 μsec compared with 1 msec, and that the fibre occupied 1 part in 16,000 of the track, compared with 1 part in 10 for a conventional electric-motor brush.

There is some evidence from the shape taken up by the fibre, that the passage of a current, of the order of 50 μA , increases the coefficient of friction. This is opposite to the effect in solid electrographite brushes; it may be a consequence of the marked temperature rise in the fibre, leading to desorption of water and other volatile species.

Conclusions

It appears that the coefficient of friction near unity observed with brushes made from several million fibres, is characteristic of the individual fibres, and not due to interaction between them. But the values as high as 9 observed occasionally may be due to interaction.

The non-linear contact resistance observed on the single-fibre, and also seen in the multiple-fibre brush, is identical to that noted on a solid-electrographite brush, if small scale

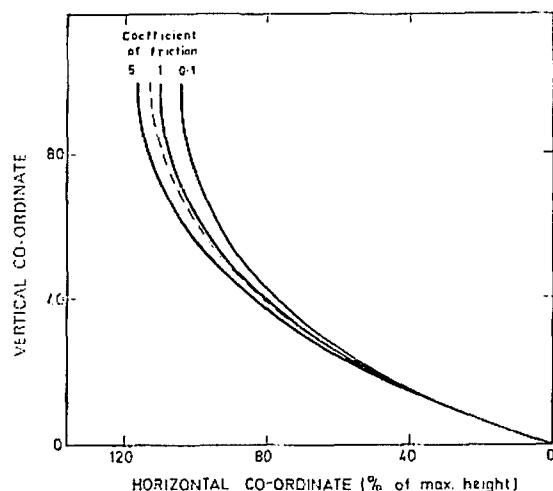


Fig. 2. Computer-drawn fibre forms at different coefficients of friction, with tracing from photograph
Contact angle 19.3° from horizontal
— — — Observed; — — — computed

TABLE I
Potential for various values of current in the low- and high-voltage regimes, V

Current, μA	15° contact angle	
	Low-voltage regime	High-voltage regime
0.5	0.5	2.3
1	0.7	2.9
2	0.9	3.5
5	1.3	4.1
10	1.55	4.6
20	1.7	5.0
50	1.85	5.55

TABLE II
Comparison of current density vs. contact potential results, V, with those for conventional electrographite brush

Current density, kA/m^2	Fibre in low-voltage regime	Fibre in high-voltage regime	Solid brush
3.4	0.5	2.3	0.2
6.8	0.7	2.9	0.3
13.6	0.9	3.5	0.5
34	1.3	4.1	0.6
68*	1.55	4.6	0.8
136*	1.7	5.0	1.0
340	1.85	5.55	1.2

*Normal operating values for solid brush

adjustments ($\times 5$ current, $\times 1.2$ voltage) are made. However, a single-fibre contact can enter a semi-insulated state in which voltages are several times higher for the same current. This may be associated with a film which the single fibre cannot remove.

Acknowledgments

The author's thanks are due to Miss S. Dove, who overcame the many experimental difficulties, to British Iron and Steel Research Association for assistance with graph plotter facilities, and to the directors of Morganite Carbon Ltd. for permission to publish this paper.

This work was carried out under an M.O.D. (Navy) Contract.

References

- 1 National Research and Development Council. B.P. 1,105,826

Appendix

Calculation of fibre form

In Fig. 3, α = angle of friction ($\tan^{-1} \mu$), H = vertical force, Q = friction force, R = resultant force.

Take co-ordinates (u , v) parallel and perpendicular to resultant force R in order to make curvature proportional to distance from axis.

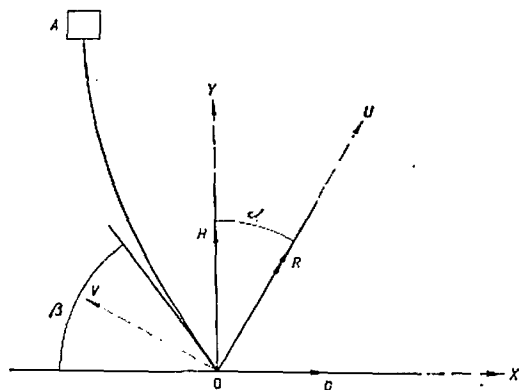


Fig. 3. Co-ordinate system in derivation of fibre form

Notation

Elliptic integrals of the first kind:

$$F(k, \varphi) = \int_0^\varphi [1 - k^2 \sin^2 \theta]^{-1/2} d\theta$$

and complete integral $K(k) = F(k, \pi/2)$

Elliptic integrals of the second kind:

$$E(k, \varphi) = \int_0^\varphi [1 - k^2 \sin^2 \theta]^{1/2} d\theta$$

and complete integral $E(k) = E(k, \pi/2)$

Fibre properties

λ = elasticity (longitudinal)

D = diameter

S = stiffness

$$S = \lambda \frac{\pi}{4} (D/2)^4 = \frac{\pi \lambda D^4}{64}$$

Equation of fibre

Curvature $v''[1 + (v')^2]^{-3/2} = -Rv/S$

Putting $p \equiv v'$:

When $u = 0$, $v = 0$

$$p \frac{dp}{dv} (1 + p^2)^{-3/2} = -Rv/S \quad p = -\cot(\alpha - \beta)$$

integrate

$$(1 + p^2)^{-1/2} = Rv^2/2S - \sin(\alpha - \beta)$$

$$\frac{du}{dv} = \frac{1}{p} = [Rv^2/2S - \sin(\alpha - \beta)] \times [1 - (\sin(\alpha - \beta) - Rv^2/2S)^2]^{1/2}$$

$$\text{put } k \equiv \left[\frac{1}{2}(\sin(\alpha - \beta) + 1) \right]^{1/2} = \cos \left[\frac{1}{2} \left(\frac{\pi}{2} - (\alpha - \beta) \right) \right]$$

$$\text{put } v \equiv 2 \sqrt{\frac{S}{R}} k \cos \varphi$$

$$dv = -2 \sqrt{\frac{S}{R}} k \sin \varphi d\varphi$$

simplifying

$$du = \sqrt{\frac{S}{R}} [(1 - k^2 \sin^2 \varphi)^{-1/2} - 2(1 - k^2 \sin^2 \varphi)^{1/2}] d\varphi$$

when $u = 0$, $v = 0$, $\varphi = \pi/2$

$$u = \sqrt{\frac{S}{R}} [2(E(k) - E(k, \varphi)) - (K(k) - F(k, \varphi))]$$

$$v = \sqrt{\frac{S}{R}} k \cos \varphi$$

converting to (x , y) co-ordinates

$$x = u \sin \alpha - v \cos \alpha$$

$$y = u \cos \alpha + v \sin \alpha$$

At top point A, $v' = \tan \alpha$

this transforms into $\varphi \equiv \varphi_1 = \sin^{-1} \left(\frac{1}{k} \sin \alpha/2 \right)$

The computer programme calculates pairs of values of x , y for 51 equally spaced values of φ , from $\frac{\pi}{2}$ (contact point) to φ_1 (top point), for specified values of contact angle β and coefficient of friction μ .

$$\begin{aligned} \text{Length of fibre } L &= \int_{\varphi_1}^{\pi/2} \left[\left(\frac{du}{d\varphi} \right)^2 + \left(\frac{dv}{d\varphi} \right)^2 \right]^{1/2} d\varphi \\ &= \sqrt{\frac{S}{R}} (K(k) - F(K, \varphi_1)) \end{aligned}$$

$$\text{hence resultant } R = (K(k) - F(k, \varphi_1))^2 \frac{S}{L^2}$$

and vertical force = $R \cos \alpha$

INSTITUTE FOR ADVANCED TECHNOLOGY

BUDGET REPORT PERIOD ENDING

May 31, 2005

HOMOPOLAR 2005 Funds

Contract No. N00014-05-1-0123	
	75,000
-	-
-	-
-	-
-	-
-	-
-	-
BUDGET ALLOCATION	75,000

**IAT ROLL-UP
SUMMARY REPORT - ALL ASSIGNMENTS**

T T ALLOCATION	75,000		BEGINNING BUDGET ALLOCATION	YTD TRANSFERS/ ADJUSTMENTS	ADJUSTED BUDGET ALLOCATION	YTD COMMITMENTS	YTD EXPENDITURES	REMAINING BALANCE
	-	-						
SALARIES AND WAGES Professional, Technical, Administrative and Students			30,096.00	-	30,096.00	4,435.99	6,560.01	19,100.00
FRINGE BENEFITS (Est. Actual) Professional, Technical, Administrative and Students			5,447.00	-	5,447.00	924.31	1,364.21	3,158.48
OTHER EXPENSES			977.00	-	977.00	-	202.89	774.11
CONSULTING			-	-	-	-	-	-
TRAVEL			13,480.00	-	13,480.00	-	1,139.96	12,340.04
COMPUTER			-	-	-	-	-	-
MODIFIED TOTAL DIRECT COSTS			\$ 50,000.00	\$ -	\$ 50,000.00	\$ 5,360.30	\$ 9,267.07	\$ 35,372.63
OVERHEAD @ 50% MTDC			25,000.00	-	25,000.00	2,680.15	4,633.54	17,686.32
EQUIPMENT			-	-	-	-	-	-
EQUIPMENT / FABRICATION			-	-	-	-	-	-
TUITION			-	-	-	-	-	-
SUBCONTRACTS (50% of First \$25,000)			-	-	-	-	-	-
SUBCONTRACTS (50% of First \$25,000)			-	-	-	-	-	-
GRAND TOTAL			\$ 75,000.00	\$ -	\$ 75,000.00	\$ 8,040.45	\$ 13,900.61	\$ 53,058.95

INSTITUTE FOR ADVANCED TECHNOLOGY
BUDGET REPORT PERIOD ENDING
May 31, 2005

2005 FUNDS

CONTRACT NO. N00014-05-1-0123	75,000
BUDGET ALLOCATION	75,000

26-1301-53xx		Homopolar Brush 12/1/04 - 10/31/05	
BEGINNING BUDGET ALLOCATION	YTD TRANSFERS/ ADJUSTMENTS	ADJUSTED BUDGET ALLOCATION	REMAINING BALANCE

SALARIES AND WAGES Professional, Technical, Administrative and Students	30,096.00	30,096.00	4,435.99	6,560.01	19,100.00
FRINGE BENEFITS (Est. Actual) Professional, Technical, Administrative and Students	5,447.00	-	5,447.00	924.31	3,158.48
OTHER EXPENSES	977.00	977.00	-	202.89	774.11
CONSULTING	-	-	-	-	-
TRAVEL	13,480.00	13,480.00	-	1,139.96	12,340.04

MODIFIED TOTAL DIRECT COSTS	\$ 50,000.00	\$ -	\$ 50,000.00	\$ 5,360.30	\$ 9,267.07	\$ 35,372.63
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OVERHEAD @ 50% MTDC	25,000.00	-	25,000.00	2,680.15	4,633.54	17,686.32
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EQUIPMENT	-	-	-	-	-	-
EQUIPMENT / FABRICATION	-	-	-	-	-	-
TUITION	-	-	-	-	-	-
SUBCONTRACTS - (50% of First \$25,000)	-	-	-	-	-	-
	-	-	-	-	-	-
	-	-	-	-	-	-
	-	-	-	-	-	-
	-	-	-	-	-	-
	-	-	-	-	-	-
	-	-	-	-	-	-

GRAND TOTAL	\$ 75,000.00	\$ -	\$ 75,000.00	\$ 8,040.45	\$ 13,900.61	\$ 53,058.95
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INSTITUTE FOR ADVANCED TECHNOLOGY

BUDGET REPORT PERIOD ENDING May 31, 2005

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
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Funding (\$K):

Projected Funding (\$K)	-	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00
Actual Task Funding (\$K)	-	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00

Execution Plan (\$K):

Direct Labor	-	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74
Fringe	-	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Operating Expenses	-	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Travel	-	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23
Consulting	-	-	-	-	-	-	-	-	-	-	-
Computing Costs	-	-	-	-	-	-	-	-	-	-	-
MTDC	-	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55
Overhead	-	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27
ARL Coop/MIPR/Subcontr(w/ O/H)	-	-	-	-	-	-	-	-	-	-	-
Equipment	-	-	-	-	-	-	-	-	-	-	-
Fabrication/Testing	-	-	-	-	-	-	-	-	-	-	-
Tuition/Fees	-	-	-	-	-	-	-	-	-	-	-

Expenditures (\$K):

Planned Monthly Total	-	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82
Planned Running Total	-	6.82	13.64	20.45	27.27	34.09	40.91	47.73	54.55	61.36	68.18
Actual Monthly Total	-	-	-	-	3.70	3.64	6.55	-	-	-	-
Actual Running Total	-	-	-	-	3.70	7.35	13.90	-	-	-	-

Commitments (\$K):

Actual Monthly Total	-	-	-	3.70	3.70	4.76	8.04	-	-	-	-
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Accruals (\$K):

Commitments + Expenditures	-	-	-	3.70	7.41	12.11	21.94	-	-	-	-
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Homopolar Motor Brush Development Studies Period ending May 31, 2005

